

NEXT GENERATION FIRE SUPPRESSION TECHNOLOGY PROGRAM STRATEGY

Department of Defense

Office of the Deputy Under Secretary of Defense
(Science and Technology)

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Executive Summary

This document is an update of *Next-Generation Fire Suppression Technology: Strategy for a National Program*, which was issued by the Office of the Director, Defense Research and Engineering in October, 1996.

Fires and explosions continue to be among the greatest threats to the safety of personnel and the survivability of military aircraft, ships, and land vehicles in peacetime and during combat operations. For these, halon 1301 (CF_3Br) had been the fire suppressant of choice. However, production of halon 1301 was banned as of January 1, 1994 due to its high ozone-depleting potential (ODP). The DoD is relying on a "bank" of halon 1301 as a temporary means of continuing protection during the search for alternatives. Spurring that search is the United Nations finding that the non-release of all halons would speed the recovery of the ozone layer.

Aggressively seeking alternatives to halon 1301, by 1997 the DoD had identified the best available replacements. Each of these was demonstrated to have potential, but each also had unresolved operational features that compromised its implementation. Recognition of these limitations led to the formulation of a new research program to develop improved options.

In 1997, the Next Generation Fire Suppression Technology Program (NGP) was initiated to develop and demonstrate, by 2004, retrofitable, economically feasible, environmentally acceptable, and user-safe processes, techniques, and fluids that meet the operational requirements currently satisfied by halon 1301 systems in existing weapons systems. The new technologies would be of low mass and volume and compatible with the host weapons system design. Any new chemicals must have high suppression efficiency and perform well in evaluations of ODP, global warming potential, atmospheric lifetime, reignition quenching, residue level, electrical conductivity, corrosivity to metals, polymeric materials compatibility, long-term storage stability, toxicity of the chemical and its combustion and decomposition products, speed of dispersion, and occupational safety requirements. These numerous requirements were a challenge to the R&D community. The research approach was organized into 6 Technical Thrusts:

1. **Risk Assessment and Selection Methodology** develops a process for research program managers to choose among alternative technologies for each application.
2. **Fire Suppression Principles** establish the mechanisms of flame extinguishment, leading to new approaches for fire control.
3. **Technology Testing Methodologies** develops test methods and instrumentation to obtain data on the effectiveness, toxicity, environmental impact, and materials compatibility of new suppressants and their principal degradation products during fire extinguishment.
4. **New Suppression Concepts** define new ideas in processes, techniques, and fluids for fire suppression based on chemical and physical principles.
5. **Emerging Technology Advancement** accelerates to maturity a variety of processes, techniques, and fluids that are currently under development.
6. **Suppression Optimization** develops the knowledge to obtain the highest efficiency of each candidate technology.

The NGP would be complete when the generic technical know-how existed to design cost-effective alternatives to halon 1301 systems. Success would eliminate DoD dependence on a substance no longer in production and minimize readiness impacts from future use restrictions.

The planned funding was \$46.2 M over 8 years, to come from the DoD Strategic Environmental Research and Development Program (SERDP), the Military Department Science and Technology Programs, and cost sharing from the participating laboratories. As full funding from the Military Departments was not forthcoming, the NGP goal was extended to FY2005.

Despite funding uncertainties, NGP research has been highly successful in providing both necessary understanding of fire suppression and direction for new processes, techniques and fluids. As the work progressed, the research has coalesced into the following 6 technical areas. The individual research reports and compilations of findings are accessible at the NGP web site: www.dtic.mil/ngp. The following is a listing of some of the highlights.

A. New Flame Suppression Chemistry. The NGP is developing both improved understanding to guide the search for new chemicals that perform as well as CF_3Br , but without the environmental drawback, as well as identifying candidates worthy of further consideration.

- Combining findings from current and pre-NGP research, NGP scientists have evolved a model for how fire suppressant additives quench flames.
- Using published data, quantitative structure-activity relationships, and laboratory screening tests, NGP chemists have examined families containing thousands of chemicals to identify those with desirable properties: high fire suppression efficiency, short atmospheric lifetime, and low toxicity.
 - Over a dozen bromofluoroalkenes and bromofluoroamines appear promising.
 - Iron-, manganese- and phosphorus-containing compounds have low environmental impact and high flame suppression effectiveness. Candidates can be selected on the basis of physical or toxicological properties.
 - A number of physically active chemicals might be suitable fire fighting agents. In particular, the extinguishing (molar) aerosol concentration of $\text{C}_4\text{F}_9\text{OCH}_3$ (HFE-7100), already approved as a solvent, was determined to be half that of halon 1301 gas.

B. Suppressant Screening Tests. A set of accurate tests that are quick, inexpensive, and require little agent have been developed for screening candidate suppressants. NGP research has produced:

- The first bench-scale suppression screen for measuring flame extinction by both gases and liquids, adaptable for powders.
- A screen for the effectiveness of a burst of suppressant (such as from a solid propellant gas generator, SPGG), both in quenching open flames and those stabilized behind an obstruction. Preliminary tests with an SPGG injection system have been successful.
- A hierarchical roadmap through the properties involved in screening for toxicity, compatibility with storage container and weapons systems materials, and environmental impact. The roadmap identifies the best screening tests for the key properties.

- Completion of a computer model to evaluate the inhalation hazard resulting from short exposures (e.g., from an accidental discharge) to a suppressant. Developed for halocarbons, the model can be extended to other suppressants with diverse toxic effects.

C. New and Improved Aerosol and Powder Suppressants. For some applications, clean (volatile) suppressants are not essential. NGP research is directed at finding new approaches to condensed phase candidates and ways to improve the use of current suppressants. NGP research has shown that:

- For the highly efficient alkali metal powders, surface area controls the rate of release of chemically active K and Na atoms into the flame. The particle size and density dictate how efficiently the particles reach the flames.
- It is possible to store a practical mass of a highly efficient, but otherwise undesirable (e.g., toxic) chemical on an inert particle and transport it safely to the fire.
- For fluids, proper droplet size is key to determining suppressant effectiveness. Fine droplets can flow around obstacles, but can evaporate early, so their vaporization is not available to cool the flame. Large droplets hit surfaces in their path and are less likely to reach the flames and may even pass through the flame without fully evaporating.
- Water droplets that evaporate near a flame are as effective as halon 1301 on a mass basis. Tests and calculations show that droplets with diameters under 20 μm evaporated in passing through thin laboratory flames, while many with diameters over 30 μm survived.

A unique set of computer programs for estimating thermophysical property data for fluids is now operational for assessing costly or commercially unavailable fluids on the computer.

D. Better Suppressant Delivery. This comprises improving the efficiency of getting the suppressant to the site of the fire through equipment clutter and unsteady, three dimensional air flows. Results include:

- A new, validated computer code for the prediction of transient, two-phase flows through a complex pipe run, enabling determination of the change in discharge rate when substituting a new suppressant into the current piping.
- A new, validated model to describe the rate of agent entrainment into flames behind different shapes of obstructions. Traditional halon 1301 systems have been overdesigned to compensate for these fires.
- Two approaches for SPGGs with increased flame suppression efficiency, yet reduced jet temperatures and momentum: additive-enhanced propellant formulations and entrainment of a chemically active additive into the effluent stream.

E. Viability of New Suppression Technologies. Improved instrumentation in the test articles owned by the Military Department laboratories is important for relating bench- and full-scale tests. NGP research has produced:

- A sensor for measurement and detection of combustible mixtures of oxygen and hydrocarbon fuels during a 250 ms fire suppression event. These measurements are especially important after suppression in order to assess the possibility of reignition.

- Two approaches to measuring suppressant concentration based on laser-induced breakdown spectroscopy and infrared absorption.
- The first *in situ*, time-dependent measurements of HF, its dissipation, and its amelioration by additives to the suppressant have now been recorded. HF is a corrosive and toxic product of any of the fluorinated fire suppressants (e.g., HFC-227ea and HFC-125) and is a principal deterrent to the deployment of these agents.

NGP fire suppression technologies must also be economically feasible. Accordingly, the NGP is nearing completion of a methodology to quantify a fire suppression technology by its life cycle cost and to enable superimposing on this a subjective value system.

F. Improved Fuel Tank Inertion. Research in this area has been limited. Only two aircraft, the F-16 and the F-117, currently use halon 1301 to inert fuel tanks when entering combat. The Air Force is seriously considering choosing CF₃I for this application. Should they do so, then alternative technologies for fuel tank inerting would not be an NGP task. Nonetheless, to be prepared, NGP staff have completed a small project to assess the current status of alternate systems that had in prior decades shown promise for fuel tank inerting.

In November 1999, in the wake of continuing disagreement over the appropriate level of funding, agreement was reached on a reduced-scale NGP of \$20.2 M. The new goal became:

“Develop and demonstrate, by 2005, technology for economically feasible, environmentally acceptable and user-safe processes, techniques, and fluids that meet the operational requirements currently satisfied by halon 1301 systems in aircraft.”

The focus on aircraft fire suppression emerged from the following:

- The aircraft safety and survivability engineering teams from all three Services have fire suppression needs for engine nacelles and dry bays that were not being addressed by S&T efforts outside the NGP.
- The Army has solutions for both current and planned ground vehicles that needs only engineering for implementation.
- The Navy has no current plans to retrofit current ships and has an S&T program in water mist technology for forward fit.

Thus, the revised NGP addresses the fires that the military customers identify as most needing additional research. Research issues that arise in adapting fire suppression technologies for ground or sea platforms will need to be addressed by the responsible Military Department.

By the final expenditure of FY2000 funds, the NGP will deliver understanding of how chemicals must interact with flames to be comparable to halon 1301 in quenching efficiency, analysis of the world of useful chemicals, identification of the best places to look for alternative suppressants and a first set of “best looks,” a suite of screening tests and guidance for their use, and a method for determining and comparing the life-cycle costs of new fire suppression technologies.

From that point forward, the NGP will be directed toward two targets.

1. New Flame Suppression Chemicals

This will extend the examination of those chemical families that show promise of successful candidates. This includes further evaluation of some families already identified as having high potential, e.g., tropodegradable bromocarbons and phosphorus-containing compounds, and families not yet systematically evaluated, e.g., nitrogen-containing compounds, copper-, manganese- and tin-containing compounds, and iodine-containing compounds. The research will identify trends in suppression effectiveness, toxicity, etc. using NGP screening methods and QSARs from prior work. The optimal candidates will be flagged for further development.

The reduced funding level limits the extent to which individual chemicals can be pursued:

- Extensive and costly testing for full toxicological examinations will not be performed.
- A few real-scale tests will be conducted to demonstrate the reliability of the bench-scale results as a predictor of the success of agents, rather than full characterization of the performance of all candidate agents

2. Improved Suppressant Storage and Delivery

Empirical tests have shown that changes in the geometry of agent release can reduce the mass of agent needed for suppression. Concurrently, NGP research has related suppressant flow properties to the enhanced concentrations needed for the quenching of flames in cluttered spaces and has shown the importance of the location where a suppressant fluid vaporizes.

The NGP will now combine these effects in a model of the interactions between the suppressant and the fire in cluttered spaces. This will identify optimal dispensing conditions, nozzle locations, etc. for suppression of fires in diverse engine nacelle and dry bay configurations. Further work will develop new ways of controlling suppressant discharge properties, approaches complementary to the traditional pressurized fluid bottles. Combined, these will constitute a set of source terms for the above model and offer flexibility and efficiency to the platform designer.

Again, the reduced funding limits the extent to which concepts for efficient storage and delivery can be examined.

- The NGP will perform a modest number of indicative real-scale experiments to demonstrate the effectiveness of the new distribution principles, rather than rigorously establishing the validity of the models.
- These tests will mainly be monitored using video cameras. The instrumentation to establish model validity will not be developed or adapted.
- These models and technologies will be turned over to the platform managers for optimization testing in their particular configurations.

The prognosis for successfully meeting the revised NGP goal is excellent, given the technical infrastructure and cadre of experts already advanced by the NGP. The Department of Defense will then need to set in place the programs to develop the new technologies for implementation in its fleet of aircraft

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I. Introduction

This document is an update of *Next-Generation Fire Suppression Technology: Strategy for a National Program*, which was issued by the Office of the Director, Defense Research and Engineering in October, 1996. The reader should examine that document for a full understanding of the DoD rationale for and approach to research to replace halon 1301 with technologies of comparable performance.

Since that date, the commercial context in which the search for alternatives to halon 1301 is proceeding has sharpened. A number of facilities have ceased fire protection, installed water sprinklers, or converted to one of the marketed halon alternatives, notably hydrofluorocarbons (HFCs) or mixtures of inert gases. Some have converted to blends of chemicals that include ozone-depleting hydrochlorofluorocarbons (HCFCs), even though these are slated for phase-out.

There remain a small number of essential uses of halon 1301 (in national defense and commercial aviation) for which suitable alternative technologies have not yet been found. For these, the desire for space- and weight-efficient alternatives continues. To the extent that these technologies might involve new chemicals, those chemicals must have significant attributes beyond high fire suppression efficiency. They must also perform well in evaluations of their ozone depletion potential (ODP), global warming potential (GWP), atmospheric lifetime, reignition quenching, residue level, electrical conductivity, corrosivity to metals, polymeric materials compatibility, stability under long-term storage, toxicity of the chemical and its combustion and decomposition products, speed of dispersion, and safety and occupational health requirements. This multiplicity of requirements continues to present a challenge to the R&D community.

The DoD Next Generation Fire Suppression Technology Program (NGP) is still the largest effort focussed on finding fire suppression technologies alternate to the use of halon 1301. There is a little research in the European Community, some work on the use of water sprays, and an occasional new candidate offered by commercial firms. NGP researchers are capitalizing on these other efforts.

NGP research has made considerable technical progress in the nearly four years since its inception. The individual research reports and compilations of findings are accessible at the NGP web site: www.dtic.mil/ngp. The following text presents the evolution of the NGP in response to that technical progress and to commercial and political changes. It begins by reiterating the motivation for the NGP, then presents the evolution of the NGP from its inception, summarizes the NGP research accomplishments to date, denotes the change in NGP scope beginning in FY2000, and delineates the NGP strategy from that point forward.

II. Prior DoD Halon Alternatives Research

A. Background

Fires and explosions continue to be among the greatest threats to the safety of personnel and the survivability of military aircraft, ships, and land combat vehicles in peacetime and during combat operations. For the past three decades, halon 1301 (CF₃Br) had been the agent of choice for fire extinguishment and explosion suppression (hereafter referred to collectively as fire suppression) in both weapon systems and facilities in the DoD, the private sector, and for other countries' armed forces and domestic needs. The DoD applications are shown in Table 1.

Table 1: Fielded Weapon Systems Applications for Halon 1301

Army	Navy/Marine Corps	Air Force
Ground Armored Vehicles - crew compartments - engine compartments	Shipboard - propulsion machinery - flammable liquid storerooms - fuel pump rooms - emergency generator rooms	Aircraft - engine nacelles - dry bays - fuel tanks - weapon bays - cargo bays
Aircraft - engine nacelles - APU compartments		Facilities
Maritime Craft	Aircraft - engine nacelles - dry bays - fuel tanks - crew compartments	Hand-held Extinguishers
Hand-Held Extinguishers - air/ground/maritime		
Communications Shelters	Ground Armored Vehicles - crew compartments - engine compartments	
	Hand-held Extinguishers	

Due to its high ozone-depleting potential (ODP), halon 1301 was banned from production as of January 1, 1994 by the 1992 Copenhagen Amendments to the 1987 Montreal Protocol on Substances That Deplete the Ozone Layer. Both domestically under the guidance of the Environmental Protection Agency (EPA) and internationally under the guidance of the United Nations Environmental Program (UNEP), the fire suppression community has committed to reducing its dependence on this chemical. There now exist a limited number of essential halon 1301 uses - those which are of paramount importance and for which no functional replacement exists. The stewards of such uses (e.g., the DoD, NASA, the commercial aircraft industry) have created "banks" of existing and recycled halon 1301 as a temporary means of continuing protection while a search for viable alternatives is pursued.

The DoD in particular adopted an aggressive policy concerning technology efforts aimed at seeking alternatives to ozone-depleting substances (ODSs). In the February 13, 1989 directive, it was stated that DoD Components "... shall conduct R&D to identify or develop alternate

processes, chemicals, or techniques for functions currently being met by CFCs and halons;" that the Director, Defense Research and Engineering (DDR&E) "... shall coordinate R&D programs, as appropriate, on alternative chemicals or technologies for fire and explosion suppression and, if necessary, other CFCs;" and that the Military Departments and Defense Agencies "... shall conduct R&D programs, as needed, to support mission requirements, with emphasis on substitutes for halons."

B. Halon Alternatives R&D Steering Group (HASG)

The Director, Defense Research and Engineering, established the HASG in September 1991 to formulate (and oversee the execution of) an integrated DoD near-term technology strategy and technology development plan to identify suitable alternatives for all ODSs.

- Chair: Director, Advanced Technology, in the Office of the Director, Defense Research and Engineering (ODDR&E)
- Vice-chair: Deputy Director, Operational Test and Evaluation/Live Fire Testing (DDOTE/LFT), Office of the Secretary of Defense
- Vice-chair: Staff Specialist for Survivability, Office of Strategic and Tactical Systems/Air Warfare (ODDS&TS/AW), Office of the Under Secretary of Defense for Acquisition and Technology (OUSD(A&T)).

C. Initial Technology Strategy and Technology Development Plan

The HASG formulated the *DOD Technology Strategy For Alternatives To Ozone- Depleting Substances For Weapon Systems Use*, approved by the DDR&E on August 31, 1992, to guide the near-term investigation and performance testing of commercially available chemicals: CFCs currently used in weapon systems applications for refrigeration and environmental control, and for general and precision cleaning, as well as the halons used for fire fighting. The HASG then developed an execution plan, the *DOD Technology Development Plan for Alternatives to Ozone-Depleting Substances for Weapon Systems Use (TDP)*, which was approved by the DDR&E on June 28, 1993 and was updated annually. Executed by the Army, Navy and Air Force, the Strategy and the TDP together formed the overall DoD near- term response to the impact of the Montreal Protocol on weapon systems.

Research under the TDP was completed in FY 1997, and the reader is referred to the document: *Technology Development Plan for Alternatives to Ozone-Depleting Substances for Weapons System Use: Final Report (September, 1998)*. The successes for firefighting were of major consequence:

- two suppressants, NaHCO₃ powder and HFC-227ea (C₃ F₇H) were identified as candidates for the engine compartments in ground vehicles;
- water mist and HFC-227ea were identified for shipboard machinery spaces and storage compartments; and
- HFC-125 (C₂ F₅H) and solid propellant-based inert gas generators were identified for aircraft engine nacelles and dry bays.

Each of these was demonstrated to be a viable approach, and design equations were developed for a few applications. However, water mist systems were shown to need further research before they could assure fire control in general shipboard applications. Inert gas generators also needed further development to overcome the hazards of excessive heat generation and ejection jet intensity. HFC-125 and HFC-227ea each have storage volume and weight penalties 2-3 times that of an equivalent extinguishing concentration of halon 1301. Additionally, during suppression they generate significant levels of toxic and corrosive HF.

Thus, while the TDP had arrived at alternatives for most ODSs, the best available replacements for halon 1301 had limited applicability. Some solutions could be implemented because the halon system was oversized or because the design requirements had changed. However, in many cases, the implementation of TDP technologies would require costly redesign and reconfiguration of the installed fire suppression systems and have a negative impact on weapon systems capabilities.

D. Remaining Fire Suppression System Technology Options

As the TDP progressed, it became clear that there were three fire suppression tactics for weapons system program managers: utilize identified near-term replacements, vintage the existing halon systems, or cease fire protection altogether. Each of these options presented significant trade-off considerations. The use of dissimilar fluids required costly re-engineering of the fire suppression system (and the host weapon system); the vintaging of fielded weapon systems required indefinite dependence on a substance that was no longer in production and which was subject to future environmental regulations. The abandonment of fire protection altogether was not feasible since personnel safety and weapon systems survivability are high DoD priorities. Recognition of these limitations led to a decision to formulate a successive research program focused on improved options for fire suppression in fielded weapons systems.

III. The Next Generation Fire Suppression Technology Program 1996-2000

A. Formulation

After nearly 3 years in development and review, the NGP was initiated in FY 1997 with the goal to develop and demonstrate, by 2004, retrofitable, economically feasible, environmentally acceptable, and user-safe processes, techniques, and fluids that meet the operational requirements currently satisfied by halon 1301 systems in aircraft, ships, land combat vehicles, and critical mission support facilities. The results would be specifically applicable to fielded weapon systems and would provide fire suppression technologies for preserving both life and operational assets. Successful completion of the NGP would eliminate DoD dependence on a substance no longer in national production and minimize any readiness impacts that could result if halon 1301 use restrictions were imposed in the future.

The new fire suppression technologies would be of low mass and volume and compatible with the host weapons system design. Successful candidates would also perform satisfactorily in a wide variety of tests for fire suppression efficiency, reignition quenching, ODP, global warming potential (GWP), atmospheric lifetime, suppressant residue level, electrical conductivity, corrosivity to metals, polymeric materials compatibility, stability under long-term storage, toxicity of the chemical and its combustion and decomposition products, speed of dispersion, and safety and occupational health requirements.

The research approach, developed by government, industry and academic experts, was organized into 6 Technical Thrusts and 24 Research Elements. The Research Elements, listed here, are described more fully in Appendix B of the 1996 Strategy Document.

1. **Risk Assessment and Selection Methodology** develops a process for research program managers to choose among alternative technologies for each application by applying modern decision-making techniques.
 - A. Development of Model Fires from DoD Fire Data
 - B. Ullage Inerting In-Flight Data Collection
 - C. Relative Benefit Assessment of Fire Protection System Changes
2. **Fire Suppression Principles** establish the mechanisms of flame extinguishment using detailed experimental studies and computational models, leading to new approaches for fire control.
 - A. Mechanisms of Ultra-High Efficiency Chemical Suppressants
 - B. Suppression Dynamics of Fine Droplets and Particles
 - C. Stabilization of Flames
 - D. Explosion Inhibition Processes
3. **Technology Testing Methodologies** select, adapt, and develop test methods and instrumentation to obtain data on the effectiveness, toxicity, environmental impact, and materials compatibility of new suppressants and their principal degradation products during the fire extinguishment process.
 - A. Suppression System Effectiveness Screening

- B. Agent Compatibility With People, Materials and the Environment
- C. Instrumentation for Gaseous Fuels, Oxygen, and Suppressant Concentration Measurements During Suppression of Flames and Explosions
- 4. **New Suppression Concepts** define new ideas in processes, techniques, and fluids for fire suppression based on chemical and physical principles.
 - A. Powder-Matrix Systems
 - B. Evaluation of Highly Effective Chemical Suppressants
 - C. Super-Effective Thermal Suppressants
 - D. New and More Effective Fire Suppression Technologies that are Presently Conceptual
- 5. **Emerging Technology Advancement** accelerates to maturity a variety of processes, techniques, and fluids that are currently under development.
 - A. Liquid Mist Systems
 - B. Advanced Flame Arresting Foams for Fuel Tank Inerting
 - C. Active Suppression for Fuel Tank Explosions
 - D. Advanced Propellant/Additive Development for Gas Generators
 - E. Enhanced Powder Panels
- 6. **Suppression Optimization** develops the knowledge to obtain the highest efficiency of each candidate technology.
 - A. Fire Suppressant Dynamics in the Fire Compartment
 - B. Suppressant Flow Through Piping
 - C. Mechanism of Unwanted Accelerated Burning
 - D. Development and Evaluation of Automatically Actuating Pre-Dispersed Agent Storage Containers
 - E. Full-Scale Optimization of Advanced Fire Suppression Technologies

The planned funding for the NGP was estimated to be \$46.2 M over 8 years. Support was to come from the DoD Strategic Environmental Research and Development Program (SERDP), the Military Department Science and Technology Programs, and cost sharing from the participating laboratories.

The major milestones for the NGP were:

- Description and tabulation of the broad classes of model fires to be suppressed by the end of FY 1998.
- Implementation of improved laboratory-scale test methods for measuring the performance, compatibility, and degradation of new suppressants during the fire extinguishment process during FY 1998-1999.
- Selection for further R&D of the first set of new technologies resulting from a broad public solicitation of ideas by the end of FY 1999.
- Completion of a core methodology for DoD program executives/managers to evaluate the impact of selecting alternative fire suppression systems on each weapons system by the end of FY 2001.
- Demonstration of a suite of computer models of the fire suppression processes for creating new suppression approaches and optimizing current ones (based on specific critical physical and chemical principles) by the end of FY 2001.
- Identification of next-generation mist, inert gas generator, and powder technologies by the end of FY 2001.
- Establishment of engineering models for an array of techniques to optimize the use of next-generation fire suppression technologies by the end of FY 2004.
- Demonstration of the effectiveness of a wide variety of new technologies and/or techniques over the period FY 1999-2004.

The NGP technology development process was considered to be complete when the generic technical know-how existed to design cost-effective alternatives to halon 1301 systems.

B. Operation

In 1996, Dr. Richard G. Gann of the National Institute of Standards and Technology was appointed as Technical Program Manager. The following were appointed as members of the Technical Coordinating Committee:

Mr. Michael J. Bennett, AFRL
Dr. William L. Grosshandler, NIST
Dr. Andrzej W. Miziolek, ARL
Dr. Ronald S. Sheinson, NRL

In 1998, Mr. Martin L. Lentz of AFRL replaced Mr. Bennett, and in 1998, Mr. E. Lawrence Ash of NAVAIR was added to the TCC.

The HASG provided program oversight to the NGP. It met annually to review program progress, coordinated the recommended next-year program and solicitations for new proposals, and forwarded the proposed program and solicitations to SERDP for funding consideration. In addition to the Chair and Vice-chairs listed above, the HASG included members from:

- the Office of the Deputy Under Secretary of Defense for Environmental Security
- the Military Departments
- DoD Agencies
- liaison personnel from other Federal agencies.

Gamboa International Corporation continued to provide the HASG Secretariat and was selected to serve as the NGP Program Support Office.

Each year, the topics for new research were selected by the TCC, with review from the HASG, and SERDP. Proposals were solicited broadly from government laboratories, academia and the private sector. The proposals were peer reviewed, with the TCC formulating a program for approval by HASG and SERDP.

Communication among the research team members was enhanced by an annual autumn introduction session, an annual NGP research meeting, and extensive participation in the annual Halon Options Technical Working Conference. All NGP reports and publications are posted on an NGP web site, www.dtic.mil/ngp.

C. Evolution of NGP Funding

NGP research began as planned in the start-up year of FY1997, with funding from SERDP and cost sharing from the participating laboratories. A successful solicitation for a full slate of projects for FY1998 was completed. However, while the Army applied some funds to the FY1997 and FY1998 program, it became clear that full funding from the three Military Department Science and Technology Programs would not be forthcoming. As an interim consequence, the NGP goal was extended to FY2005, and a number of projects that had been approved to begin in FY1998 were deferred to future years.

Further solicitations for proposals were conducted for FY1999 and FY2000. No funding from the three Military Department Science and Technology Programs materialized. Thus, a number of approved projects were again deferred.

D. Environmental Developments

The international community responded dramatically to the potential for severe environmental hazard from depletion of the earth's ozone layer. Replacements for refrigerants and solvents were identified and implemented. The use of the halon fire suppressants was greatly reduced by a number of measures:

- implementing the use of alternative agents for those applications where commercial chemicals were feasible,
- eliminating fire protection altogether in some applications,
- using non-ozone-depleting chemicals for fire fighting training, for certifying halon systems, etc.

In 1994, the UNEP announced that just after the turn of the century, the mass of chlorine and bromine (and the accompanying ozone depletion) in the stratosphere would have peaked and

would begin to diminish. Their report also identified four principal actions that would speed this decrease. The second most effective of these was the non-release of all halons currently in existing equipment. This was a clear signal to the fire protection community that the world was watching the effort to identify and implement alternatives to the halons and that an accelerated phase-out was a clear possibility. In related activity, research was underway to develop processes for the economical conversion of the halogenated hydrocarbons into other useful chemicals.

As the ozone depletion threat was being successfully addressed, worldwide concerns over global warming continued to rise. These culminated in the drafting of the Kyoto Accords late in 1997. While these have not yet been universally accepted and while no action plans for reducing greenhouse emissions have been implemented, this document makes it essential that current and future chemicals be examined for their absorption of infrared solar radiation.

The reality of both stratospheric and tropospheric impact of released chemicals led to the general recognition of atmospheric lifetime as a principal property for consideration in the development of alternatives. Focusing on chemicals that did not persist in the environment would provide some assurance that they would not be major factors in ODP, GWP, and any future deleterious environmental effects.

IV. NGP Program and Technical Progress

NGP research has been highly successful in providing both necessary understanding of fire suppression and direction for new processes, techniques and fluids. As the work progressed, the research has coalesced into 6 technical areas:

- New Flame Suppression Chemistry
- Suppressant Screening Tests
- New and Improved Aerosol and Powder Suppressants
- Viability of New Suppression Technologies
- Better Suppressant Delivery
- Fuel Tank Inertion

Table 1 shows a listing of the project titles. A crosswalk with the original Thrusts and Research Elements can be discerned from the project numbers. These have the code: AB/C/xxx, where A is the Thrust number, B is the Research Element letter, C is the sequential number of project under that Research Element, and xxx are the last numbers of the fiscal years that the project was supported.

Table 1. NGP Project Titles and Investigators

1A/1/78.	DEVELOPMENT OF MODEL FIRES FOR FIRE SUPPRESSION RESEARCH Principal Investigator: Anthony Finnerty, ARL Associate Investigators: James Tucker, AFRL and Juan Vitali, ARA; Ronald Sheinson, NRL
1C/1/890.	RELATIVE BENEFIT ASSESSMENT OF FIRE PROTECTION SYSTEM CHANGES Principal Investigator: Michael Bennett, Eglin AFB
2A/1/7890, /2/890.	MECHANISMS OF ULTRA-HIGH EFFICIENCY CHEMICAL SUPPRESSANTS Principal Investigator: Kevin McNesby, ARL Associate Investigator: James Fleming, NRL
2B/1/7890.	SUPPRESSION EFFECTIVENESS OF AEROSOLS AND PARTICLES Principal Investigator: Ronald Sheinson, NRL
2B/2/89.	DROPLET INTERACTIONS WITH HOT SURFACES Principal Investigator: Yudaya Sivathanu, En'Urga, Inc. COR: William Grosshandler
2B/3/89.	TECHNICAL SUPPORT FOR THE STUDY OF DROPLET INTERACTIONS WITH HOT SURFACES Principal Investigator: Jiann Yang, NIST
2C/1/789.	STABILIZATION OF FLAMES Principal Investigator: Vincent Belovich, AFRL
3A/1/789.	DISPERSED LIQUID AGENT FIRE SUPPRESSION SCREEN Principal Investigator: Jiann Yang, NIST
3A/2/890.	TRANSIENT-APPLICATION-RECIRCULATING-POOL-FIRE AGENT EFFECTIVENESS SCREEN Principal Investigator: William Grosshandler, NIST
3B/1/89.	TOXICOLOGICAL ASSESSMENT OF HUMAN HEALTH CONSEQUENCES ASSOCIATED WITH INHALATION OF HALON REPLACEMENT CHEMICALS Principal Investigator: Darol Dodd, AFRL
3B/2/8.	AGENT COMPATIBILITY WITH PEOPLE, MATERIALS AND THE ENVIRONMENT Principal Investigators: Marc Nyden, NIST Stephanie Skaggs, Universal Technical Services
3C/1/789.	LASER-BASED INSTRUMENTATION FOR REAL-TIME, IN-SITU MEASUREMENTS OF COMBUSTIBLE GASES, COMBUSTION BY-PRODUCTS, AND SUPPRESSANT CONCENTRATIONS Principal investigator: Kevin McNesby, ARL
3C/2/890.	FAST RESPONSE SPECIES CHARACTERIZATION DURING FLAME SUPPRESSION Principal Investigator: George Mulholland, NIST

4A/1/89. POWDER-MATRIX SYSTEMS
Principal Investigators: Gregory Linteris, NIST

4B/1/8. TROPODEGRADABLE BROMOCARBON EXTINGUISHANTS
Principal Investigator: J. Douglas Mather, NMERI
COR: Ronald Sheinson

4B/2/8,4D/3/7. FLAME INHIBITION BY PHOSPHORUS-CONTAINING COMPOUNDS
Principal Investigator: Elizabeth M. Fisher, Cornell University
COR: Andrzej Miziolek, ARL

4B/3/890. ENVIRONMENTAL IMPACT OF NEW CHEMICAL AGENTS FOR FIRE SUPPRESSION
Principal Investigators: Robert Huie, NIST, and Andrzej Miziolek, ARL

4B/4/0. PERFORMANCE DATA ON COLD TEMPERATURE DISPERSION OF CF₃I AND ON MATERIALS COMPATIBILITY WITH CF₃I
Principal Investigator: Jiann Yang, NIST

4B/5/0. ASSESSMENT OF COMPLETENESS OF SEARCH FOR ALTERNATIVE SUPPRESSANT CHEMICALS
Principal Investigator: Richard G. Gann, NIST

4C/1/890. SUPER-EFFECTIVE THERMAL SUPPRESSANTS
Principal Investigator: William M. Pitts, NIST

4D/1/7. ELECTRICALLY CHARGED WATER MISTS FOR EXTINGUISHING FIRES
Principal Investigator: Charles H. Berman, Titan Corp.
COR: Ronald Sheinson, NRL

4D/2/7. IDENTIFICATION AND PROOF TESTING OF NEW TOTAL FLOODING AGENTS
Principal Investigator: Robert E. Tapscott, NMERI
COR: Andrzej Miziolek, ARL

4D/4/7. DEVELOPMENT OF A SELF ATOMIZING FORM OF WATER
Principal Investigator: Richard K. Lyon, EER, Inc.
COR: William Grosshandler, NIST

4D/5/8. MAIN GROUP COMPOUNDS AS EXTINGUISHANTS
Principal Investigator: J. Douglas Mather, NMERI
COR: Ronald Sheinson, NRL

4D/6/8. DUAL AGENT APPROACH TO CREW COMPARTMENT EXPLOSION SUPPRESSION
Principal Investigator: Douglas Dierdorf, ARA Corp.
COR: Andrzej Miziolek, ARL

4D/7/8. DENDRITIC POLYMERS AS FIRE SUPPRESSANTS
Principal Investigator: Nora Beck Tan, ARL

4D/13. EFFECTIVE, NON-TOXIC METALLIC FIRE SUPPRESSANTS
Principal Investigator: Gregory Linteris, NIST

4D/14. FLUOROALKYL PHOSPHOROUS COMPOUNDS
Principal Investigator: Robert Tapscott, NMERI

4D/15/0.	TROPODEGRADABLE BROMOCARBON EXTINGUISHANTS II Principal Investigator: J. Douglas Mather, NMERI COR: Ronald Sheinson, NRL
4D/17/0.	A METHOD FOR EXTINGUISHING ENGINE NACELLE FIRES BY USE OF INTUMESCENT COATINGS Principal Investigator: Ginger Bennett, Booz-Allen COR: Martin Lentz, Eglin AFB
5A/1/0.	PARAMETRIC INVESTIGATION OF DROPLET ATOMIZATION AND DISPERSION OF LIQUID FIRE SUPPRESSANTS Principal Investigator: Cary Presser, NIST
5C/1/9.	ACTIVE SUPPRESSION FOR FUEL TANK EXPLOSIONS Principal Investigator: Leonard Truett, Eglin AFB
5D/1/90.	ADVANCED PROPELLANT/ADDITIVE DEVELOPMENT FOR GAS GENERATORS Principal Investigator: Gary Holland, Primex Aerospace Associate Investigator: Russell Reed, NAWC-WPNS COR: Lawrence Ash, NAVAIR
5E/1.	ENHANCED POWDER PANELS Principal Investigator: John Vice, Skyward, Inc. COR: Marty Lentz, Eglin AFB
6A/1/0.	FIRE SUPPRESSANT DYNAMICS IN THE FIRE COMPARTMENT Principal Investigator: David Keyser and Lawrence Ash, NAVAIR
6B/1/89.	SUPPRESSANT FLOW THROUGH PIPING Principal Investigator: John Chen, Lehigh University COR: William Grosshandler, NIST
6C/1.	MECHANISM OF UNWANTED ACCELERATED BURNING Principal Investigator: William Pitts, NIST

The following is a brief summary of the key NGP research accomplishments to date. For more detail, the reader is referred to the NGP Annual Reports at the NGP web site.

A. New Flame Suppression Chemistry

An economical way to effect retrofit of a fire suppression system would be with a new chemical that performs as well as CF₃Br, but without the environmental drawback. The NGP is developing both improved understanding to guide the search as well as identifying candidates worthy of further consideration.

1. Combining findings from current and pre-NGP research, NGP scientists have evolved a model for how fire suppressant additives quench flames. Flame propagation relies on fast reactions of the free radical pool (OH radicals and O and H atoms) with fuel molecules. In

uninhibited flames, these three species are in equilibrium with each other, but are well above equilibrium with their surroundings. High efficiency suppressants (e.g., those containing bromine, phosphorous or metal atoms) catalytically reduce the radical pool to a near-equilibrium level. However, the flame can still continue to burn at these lower radical concentrations. Significant thermal mass must also be added to reduce the flame temperature and thus decrease the flame propagation kinetics to non-combustion-sustaining rates. Extinguishing concentrations thus have a lower fundamental limit, perhaps of the order of 1-2 mass percent, regardless of the degree of chemical activity.

2. Using published data, quantitative structure-activity relationships, and laboratory screening tests, NGP chemists have examined families containing thousands of chemicals to identify those with desirable properties: high fire suppression efficiency, short atmospheric lifetime, and low toxicity.

a. Compounds with a bromine atom and a tropospherically reactive chemical feature should manifest high flame suppression efficiency and low atmospheric lifetime. Eight bromofluoroalkenes have calculated atmospheric lifetimes of the order of a week and measured extinguishment concentrations not far from that of CF_3Br . Inhalation toxicity screening data, conducted by the Advanced Agent Working Group, indicates that 4 of these show no aftereffects in rats from a 15-minute exposure to 5 volume percent. An additional 8 bromofluoroamines also appear promising.

b. The phosphorus atom is effective in flame retardancy and phosphorus-containing chemicals (PCCs) should have low environmental effect. NGP research indicates that most PCCs should show high flame suppression effectiveness, largely determined by phosphorus loading, so candidates can be selected on the basis of physical or toxicological properties.

c. Examination of over 1500 thermal agents identified about 25 compounds which might be suitable fire fighting agents, some of which are already in use. A variety of families including ethers, furans, amines, and straight-chain hydrocarbons are represented, almost all highly fluorinated. In particular, $\text{C}_4\text{F}_9\text{OCH}_3$ (HFE-7100), already approved by EPA as a solvent, shows promise. Calculations indicate it is environmentally benign. Using the Dispersed Liquid Agent Screen (see Screening Tests below), the extinguishing (molar) concentration of the aerosol was determined to be half that of halon 1301 gas.

d. To enable quantification of this aerosol evaporation effect, NGP research has developed two devices (an electrostatic atomization system and an inductively coupled plasma nebulizer) for seeding the air streams of laboratory burners with fine droplets of controlled dimension. The ability to vary the droplet size makes it possible to study both chemical effects, after droplet vaporization, and the physical effects of the droplets.

e. Previous research had shown that $\text{Fe}(\text{CO})_5$ is a near ideal flame radical reducer, but is highly toxic. Ferrocene, a decidedly less toxic iron-containing compound, produced nearly identical results, indicating that the binding state of the iron does not alter the flame suppression behavior. Thus, future examination of iron compounds can focus on their toxicity and their physical properties.

f.. A flame quenching mechanism for manganese-containing compounds was developed. It showed that these known combustion modifiers operate chemically like iron-containing compounds.

B. Suppressant Screening Tests

Of the large number of chemicals to be considered in the search for replacement suppressants, many can be discarded based on available information. For the rest, screening tools are needed to identify those relatively few agents that should be investigated aggressively. A set of accurate screens that are quick, inexpensive, and require little agent will be completed in calendar 2000.

1. A measure of fire suppression efficiency for high volatility (gaseous) and low volatility (liquid) fluids is mandatory. The NGP has developed the first bench-scale suppression screen for comparing the flame extinction performance of both gases and liquids and can do adapted for powders. The Dispersed Liquid Agent Screen (DLAS) is now in steady use both to obtain suppression efficiency data on candidate suppressant fluids and as a research tool. Fabrication drawings and an operations manual have been prepared for distribution to interested laboratories.
2. A second NGP apparatus can screen the effectiveness of a short burst of suppressant (such as would emerge from a solid propellant gas generator, SPGG), both in quenching open flames and those stabilized behind an obstruction. Preliminary tests with an SPGG injection system have been successful.
3. The NGP has produced a hierarchical roadmap through the maze of properties involved in screening for toxicity, with storage container and weapons systems materials, and with the environment. It also identifies the best screening tests for the key properties.
4. The NGP sponsored completion of a physiologically based pharmacokinetic (PBPK) model of a human system that incorporates a breath-by-breath description of respiration and follows the inhaled suppressant to the bloodstream. Developed for halocarbons, the model can be extended to other suppressants with diverse toxic effects.
5. Computational screening capacity tool for a suppressant's atmospheric lifetime is continuing and has been validated for halomethanes. Calculations for fluoroethanes and the ethers derived from them have reproduced the experimental trends.

C. New and Improved Aerosol and Powder Suppressants

For some applications, clean (volatile) suppressants are not essential. To this end, fine water mist and efficient powders have been the subjects of real-scale testing; however, the approaches to date have not met with universal success. As with gaseous and vapor suppressants, NGP research is directed at finding new approaches to condensed phase candidates and ways to improve the use of current suppressants.

1. Sodium and potassium bicarbonate powders are more efficient fire suppressants than halon 1301 on a mass basis. However, once released these powders obscure vision and are corrosive to some surface materials, such as aluminum. Thus alternative approaches are needed.

- a. The alkali metal atoms released when sodium or potassium bicarbonate powders decompose in a flame tie up the reactive flame radicals. The surface area of the particles controls the rate of release of these species into the flame. The powder particle size and density dictate how closely the particles follow the flame gas velocity streamlines and thus how efficiently the particles reach the flames.
 - b. It is possible to store a practical mass of a highly efficient, but otherwise undesirable (e.g., toxic) chemical on an inert particle and transport it safely to the fire. As much as 200 weight percent of $\text{Fe}(\text{CO})_5$ can be absorbed into aerogels; and at 250 °C a large fraction is desorbed. The speed of agent liberation is being determined. Pyrophoric chemicals, such as $\text{Fe}(\text{CO})_5$, are not appropriate for this type of transport, as they can react with water adsorbed on the host.
2. Nearly all suppressant fluids emerge from pressurized storage containers as liquids along with a gaseous component. The properties of the liquid (a) determine its transport effectiveness to the fire, (b) the magnitude of its effect on the flames, (c) its ability to quench condensed fuels, and (d) its impact on preventing reignition. It is not known if the optimal values of these liquid properties are uniform for these four impacts. Consideration of droplet size is especially important. Very fine droplets follow the propellant gas streamlines and thus can flow around obstacles. However, they can evaporate before reaching the flame zone, and their heat of vaporization is not available to cool the flame. Large, high-momentum droplets impact surfaces in their path, reducing their likelihood of reaching the flames. Too large droplets may pass through the flame without fully evaporating. There is thus a premium in knowing and thus specifying the optimal droplet size and velocity ranges.
 - a. If water droplets can evaporate in or near the flame, water is as effective as halon 1301 on a mass basis. NGP experiments showed that droplets with diameters under about 20 :m completely evaporated in passing through the thin flames of laboratory burners, while a significant number of droplets with diameters over about 30 :m survived. Calculations verify that water droplets with diameters under about 50 :m should evaporate near the flame front.
 - b. In storage facilities and machinery spaces, the quenching of flame spread over liquid and solid fuels is of concern. Experiments showed that flame spread decreases with the mass of water incident on the surface, with little effect of droplet diameter. However, buoyancy from the hot surface may keep small droplets from reaching the surface.
 - c. A unique set of computer programs for estimating the thermophysical property data for fluids is now operational. As the NGP examines new fluids, some not commercially available, and as solutions emerge as serious candidates (e.g., aqueous sodium lactate) these estimates will become pivotal.

D. Better Suppressant Delivery

The complement to identifying new suppressants is improving the efficiency of getting the suppressant to the site of the fire. This comprises storage and discharge technology, transport through any distribution piping and transport throughout the compartment space (with equipment

clutter and unsteady, three dimensional air flows) once the agent has been dispensed from the storage/distribution hardware.

1. Replacement fluids must function within the existing distribution plumbing to avoid the major cost of replacing the piping. NGP engineers have completed and validated a new computer code for the prediction of transient, two-phase fire suppressant flows through a complex pipe run, enabling determination of the change in discharge rate when substituting a new suppressant into the current piping.
2. Traditional halon 1301 systems have been overdesigned to compensate for (a) the transient release of the suppressant and (b) the presence of numerous obstructions or clutter. NGP engineers have developed and validated a model to describe the rate of agent entrainment into flames behind different shapes of obstructions. The model develops design criteria for the free stream agent concentration and injection period needed for extinguishment.
3. NGP research is developing new types of SPGGs that have increased flame suppression efficiency with reduced jet temperatures and momentum. One approach is to create additive-enhanced propellant formulations. A second approach directs the hot gas generator discharge from an “inert” solid propellant across an “activated” agent bed, entraining a chemically active additive into the gas stream.

E. Viability of New Suppression Technologies

1. The success of new NGP technologies requires (1) characterization of critical fire suppression parameters under real-scale weapons system fire scenarios to guide laboratory research and (2) demonstration that candidate fire suppression methods are quenching flames as they would under the threats experienced in the field. Meeting these needs entails improved instrumentation in the test articles owned by the Military Department laboratories. Making these measurements of concentrations of fuel, oxygen, the suppressant, and harmful combustion byproducts during and after the fire suppression process requires rapid data acquisition during a period of shock and vibration, high temperatures and rapidly changing flow patterns.
 - a. NGP researchers have developed a time-resolved (10 ms), multi-point, fieldable, near-infrared tunable diode laser-based sensor for measurement and detection of combustible mixtures of oxygen and hydrocarbon fuels during a fire suppression event as little as 250 ms in duration. Detection of fuel and oxygen concentration is especially important after suppression in order to predict the possibility of reignition.
 - b. Measurement of the distribution of the suppressant is essential to characterize the fire extinguishment process and for certification of a suppression system. Since there are likely to be a multiplicity of candidate agents, with potentially different capabilities of being monitored, the NGP has developed approaches based on two distinct principles: laser-induced breakdown spectroscopy and infrared absorption.
 - c. Excessive generation of HF, a corrosive and toxic degradation product of any of the fluorinated fire suppressants (e.g., HFC-227ea and HFC-125), is a principal deterrent to the deployment of these agents. The first *in situ*, time-dependent measurements of the

concentration of HF, its dissipation, and its amelioration by additives to the suppressant have now been recorded.

d. Making these measurements requires a fiber optic probe system capable of operation at high temperatures. NGP scientists have designed a probe for use at temperatures up to 1200 K in the presence of powder, smoke, and fine water mist.

e. The NGP team has also developed a cell for use in measuring the high temperature (up to 1000 K) infrared properties of candidate suppressants. This information enables finding spectral lines for detection and developing calibration curves for the temperature-dependent sensitivity of the measurements.

2. The NGP goal specifies that the new fire suppression technologies must also be economically feasible. There are many contributing factors to be considered when deciding how or whether to adopt a fire suppression system design. These include both objective cost factors and subjective value factors. Accordingly, the NGP is developing a methodology to quantify a fire suppression technology by its life cycle cost and to enable superimposing on this a subjective value system. The data gathering for and formation of the baseline (halon 1301) case has been completed, as has the structuring of the cost benefit analysis process. This provides a framework for evaluating a range of weapons systems, considering both financial and technical variables.

F. Improved Fuel Tank Inertion

Research in this area has been limited. There are only two aircraft that currently use halon 1301 to inert fuel tank when entering combat, the F-16 and the F-117. The Air Force is seriously considering the use of CF_3I for this application. Should this decision be positive, then alternative technologies for fuel tank inerting would not be an NGP task. Nonetheless, to be prepared, NGP staff are near completion of a small project to assess current status of alternate systems that had in prior decades shown promise for fuel tank inerting.

V. Reformulation of the NGP

A. Focused Goal

In November 1999, in the wake of continuing disagreement over the appropriate level of funding, agreement was reached on a reduced-scale NGP. The new goal became:

“Develop and demonstrate, by 2005, technology for economically feasible, environmentally acceptable and user-safe processes, techniques, and fluids that meet the operational requirements currently satisfied by halon 1301 systems in aircraft.”

The planned funding was to be \$20.2 M, of which \$13.6 M had been allocated during FY1997-2000.

The focus on aircraft fire suppression emerged from discussions with representatives of the Military Services:

- The aircraft safety and survivability engineering teams from all three Services stated that they have fire suppression needs for engine nacelles and dry bays that were not being addressed by S&T efforts outside the NGP.
- The Army stated that it had solutions for both current and planned ground vehicles that needed only engineering (not research) for implementation. Thus they had not budgeted S&T funds for fire suppression research in FY2000.
- The Navy stated that it had no current plans to retrofit current ships, that they release very little halon 1301, and that the DoD reserves will suffice. ONR had an approximately \$1 M/year S&T program in water mist, their planned technology for forward fit.

Thus, the revised NGP addresses the predominant fires that the military customers identify as most needing additional research: fires occurring in the aircraft dry bays and engine nacelles in both current and planned platforms. Research issues that arise in adapting fire suppression technologies for ground or sea platforms will need to be addressed by the responsible Military Department.

The Air Force has transitioned the use of CF₃I for fuel tank inerting to the F-16 Program Office, where engineering determinations of key properties are underway. The EPA has endorsed this chemical for this use. Thus, fuel tank inerting does not appear in the reduced NGP plan. It could be added if CF₃I were to prove unacceptable.

While the research is directed at solutions for aircraft, there are clear implications for other DoD applications. The technologies developed for dry bays would merit consideration for crew compartments, where the fires and suppression conditions are similar. Technologies of benefit in addressing the obstructed fires and spray fires in engine nacelles would also apply to machinery and storage spaces on ships.

B. Technical Approach of the Revised Program

Because of the substantial technical accomplishments of the initial years, the NGP has a solid base from which to develop new fire suppression technology for weapons systems. By the final expenditure of FY2000 funds, the NGP will deliver the following:

- understanding of how suppressant chemicals must interact with flames in order to be comparable to halon 1301 in quenching efficiency;
- analysis of the world of useful chemicals, identification of the best places to look for alternative suppressants, and a first set of “best looks;”
- a suite of screening tests and guidance for their use; and
- a method for determining and comparing the life-cycle costs of new fire suppression technologies.

These results complete NGP efforts under Thrust 2 (Fire Suppression Principles), Thrust 3 (Technology testing Methodologies), and Thrust 1 (Risk Assessment and Selection Criteria).

From that point forward, the NGP will be directed toward two targets.

1. New Flame Suppression Chemicals

This effort continues mainly under Research Element 4B (Evaluation of Highly Effective Suppressant Chemicals), encompassing fluid and solid candidates. Several families of chemicals have already been examined, e.g.:

- Main group compounds
- Iron-containing compounds
- Non-chemically active compounds
- Tropodegradable bromocarbons
- Phosphorus-containing compounds

In each case, some promising candidates have been identified. These will be screened further to establish legitimate options for further development. A second look at the last two families is also likely.

In addition, a recent project has examined the full realm of chemical categories, identifying those areas that have been well-studied, those that show little promise of successful candidates, and those meriting fuller study. The last set includes:

- Nitrogen-containing compounds (e.g., amines and nitrides)
- Copper-, manganese- and tin-containing compounds
- Iodine-containing compounds

Research into each of these chemical families will identify trends in suppression effectiveness, toxicity, etc. using NGP screening methods and QSARs from prior work. The optimal candidates will be flagged for further development.

The reduced funding level limits the extent to which individual chemicals can be pursued:

- Extensive and costly testing for a full toxicological examination will not be performed.
- A few real-scale tests will be conducted to demonstrate the reliability of the bench-scale results as a predictor of the success of agents, rather than full characterization of the performance all candidate agents

2. Improved Suppressant Storage and Delivery

Building on results from Thrust 2, this focus continues work under Thrusts 5 (Viability of New Suppression Technologies) and 6 (Better Suppressant Delivery). During the early years of the NGP, the Navy and Air Force aircraft safety and survivability teams have demonstrated how changes in the flow properties and geometry of suppressant release can enhance the efficiency of suppression. Concurrently, NGP research has developed principles for the relationship between suppressant flow properties and the enhanced concentrations needed for the quenching of flames in cluttered spaces. The research has also shown the importance of the location (relative to the flame) where a suppressant fluid vaporizes.

What remains, then, is the development of modeling of the interactions between the suppressant flow and the fire in cluttered spaces. This will serve as a guide for the selection of optimal dispensing conditions, nozzle locations, etc. for effective suppression of fires in the various engine nacelle and dry bay configurations.

Further work will also develop new ways of positioning the suppressant and controlling its discharge properties, approaches complementary to the traditional pressurized fluid bottles. Combined, these will then constitute a set of source terms for the above models and offer flexibility and efficiency to the platform designer.

Again, the reduced funding limits the extent to which concepts for efficient storage and delivery can be examined.

- The NGP will perform a modest number of indicative real-scale experiments to demonstrate the effectiveness of the new distribution principles, rather than rigorously establishing the validity of the models.
- These tests will mainly be monitored using video cameras. The instrumentation to establish model validity will not be developed or adapted.
- These models and technologies will be turned over to the platform managers for optimization testing in their particular configurations.

C. Additional Efforts

Over the past 4 years, the NGP has solicited proposals for “outside the box” approaches to fire suppression under Research Element 4D, “New and More Effective Fire Suppression

Technologies that are Presently Conceptual.” Some of these novel ideas have proven successful at broadening the NGP thinking. A modest continuation of these solicitations is possible.

Much of the innovation in NGP projects has resulted from interactions among a large set of investigators in diverse but related aspects of fire suppression. The number of concurrent projects, which peaked at 23, will decrease to 12 in FY2001 and to about 5 in FY2002. The NGP will continue to co-sponsor and participate actively in the spring Halon Options Technical Working Conference. The NGP will broaden the participation in its autumn Annual Research Meeting, inviting past investigators and other experts. It is hoped that these two meetings will continue to broaden the perspective and stimulate the innovation of the NGP investigators.

VI. Conclusion

The NGP has generated three types of products:

- extensive new knowledge of fire suppression of the types of fires experienced in current Department of Defense weapons systems,
- methods for screening new suppressants, and
- a number of chemicals for further examination.

Funding constraints have led to a focus of future research on fire suppression for aircraft:

- new suppressant chemicals and
- precepts for optimizing their delivery to the flames.

A methodology for determining and comparing the life-cycle costs of new fire suppression technologies in aircraft is nearing completion.

The prognosis for successfully meeting the revised NGP goal is excellent, given the technical infrastructure and cadre of experts advanced by the NGP. The Department of Defense will then need to set in place the programs to develop the new technologies for implementation in its fleet of aircraft.